Preliminary Two Dimensional Haptic Thresholds and Task Performance Enhancements

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Abstract

Many tasks may be performed with greater efficiency and speed with haptic assistance. Using the Penbased Haptic Display, a low-power, low-friction, and high-precision device, we performed two separate experiments to measure two properties of human/haptic interactions. In the first experiment, we measured the level of force at which a subject may detect the presence of haptic feedback at a 71% accuracy level using a converging adaptive threshold algorithm. The average haptic threshold of eleven subjects was 20.8 milliNewtons. The second experiment quantifies changes in task performance using Fitts' Law. We measured improvements at three force levels compared to no force.

1. Introduction

The proliferation of graphical user interfaces and advances in computational power have lead to the creation of increasingly rich application environments capable of receiving input from multiple devices, but limited to one mode of output. Eliminating this bottle-neck will facilitate more efficient interactions with these powerful applications.

Haptic peripherals allow a new modality of computer interaction and haptic forces have been proven to increase performance[5]. In this paper we explore the weakest effects that can provide meaningful information to the user. If small forces can also be shown to be useful, adding haptic interfaces to smaller systems, e.g. laptops, PDA's, and even cell phones, may help overcome these devices' input limitations.

In a previous study, an experiment was performed which measured, in one dimension, what was termed the haptic threshold[3] for a different device. This paper reports a new experiment directly descended from the earlier experiment to measure this quantity on the two dimensional Penbased Haptic Display (Figure 1).

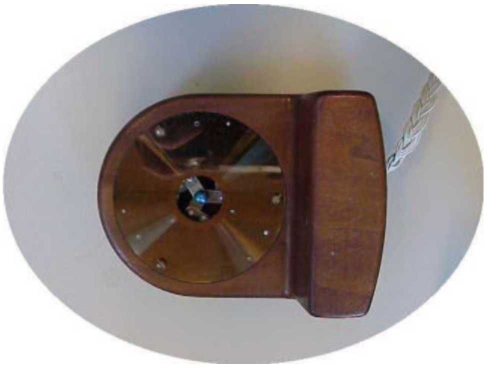

Figure 1. The Penbased Haptic Display[1] was used for these experiments. It supports planar motion within 1.5x1.5cm^2 workspace. Peak force is 1.4N and friction level is less than 10nN and resolution is higher than 0.02mm.

In this study, consisting of two experiments, we first use an adaptive threshold algorithm to measure the lowest detectable forces rendered in the horizontal plane by the Penbased Haptic Display. A subject choses which of two icons on a desktop simulation possesses haptic forces. The magnitude of force is adjusted to determine the haptic threshold.

Second, we measured path length and movement time of a task similar to a desktop icon search-and-click task. Performance factors and force applied to subjects were measured. We used Fitts' Law[4] to analyze performance. Fitts' Law relates the movement times of humans using the movement amplitude and target size.

For this experiment, the subject moved to the indicated target icon, the target changed, and the task was repeated. In one version of this experiment, all five icons had haptic forces, while in a second, only the target icon had force.

In a search-and-click task, icons other than the target that have haptic forces have been termed haptic distractors[2]. When haptics are implemented in a real world setting, many icons have forces since the target icon cannot be anticipated. We included this condition in our second experiment.

2. Methods

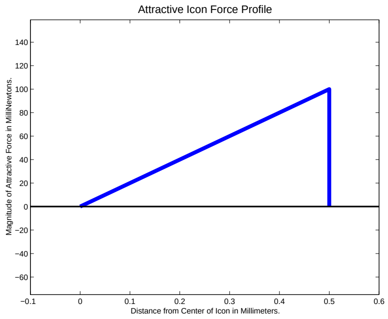

Figure 2. Icon force profile. Force exerted on the end-effector is at a maximum at the icon's edge, and zero at the icon's center. There was no force outside the icon.

We conducted two separate experiments with multiple subjects. The methods employed were designed to be consistent and comparable with our earlier 1-D experiment[3].

The first experiment used an adaptive threshold algorithm[7] which has been used to study the psychophysics of human touch as applied to Braille[6], a task similar to ours. The algorithm adjusts the level of force up and down depending on the subject's previous two responses. The experiment concludes when the subject selects which of two icons has haptic force with a specific accuracy.

Our procedure was identical to the previous one dimensional experiment, including the use of headphones to eliminate audio cues and providing every subject with a written description of the experiment at its onset. The second dimension required the addition of a two dimensional desktop simulation for visualizing the end effector and icons.

In the second experiment, we measured the amount of time it took to move between icons and press a key, (MT), for four different path lengths, (A), at four force levels (one of which was zero) for a common computer desktop search-and-click task. The icon size, (W), was 1 millimeter for all experiments. (Icons were 1 millimeter measured in the device and were displayed 7 times larger.) These measurements were then interpreted using Fitts' Law[4][5].

$$MT = a + b \log_2 \left(\frac{2A}{W} \right)$$

Both experiments used circular icons having attractive haptic virtual wells. The haptic icon attracted the end effector to the center of the icon with a force proportional to the distance between their centers'. This force was only present while the end-effector's center was within the icon (Figure 2).

The Penbased Haptic Display[1] provided the low-friction, high-precision platform for these experiments. It is characterized by less than 10 milliNewtons of backdrive friction and a minimum of 0.020 millimeters of position resolution. It possesses a workspace of 1.5 x 15 centimeters^2 in the horizontal plane and interfaces with the user's fingertip (or a pen) with a small aluminum nub.

Eleven subjects from the University of Washington pool of students, faculty and staff participated in this experiment. The group consisted of two women and nine men between the ages of 25 and 50. The University of Washington Human Subjects Review Committee approved our study and every subject signed a consent form prior to performing the experiment.

2.1. Haptic Threshold

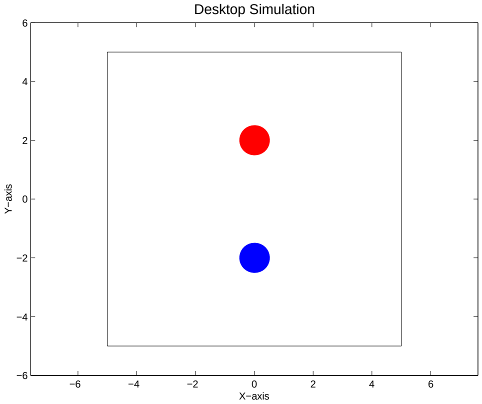

Figure 3. Screenshot of graphics for haptic threshold experiment. Vertical axis corresponds to index finger flexion/extension. Units of x and y axes ticks are millimeters in the haptic display and multiples of seven millimeters on the screen.

For the experiment, we presented two icons, one over the other, in the y-dimension (Figure 3). This configuration maintained consistency with the one dimensional experiment. Exactly one icon had a haptic force field that attracted the end-effector as described previously. The subject indicated which icon had force by pressing a key with their other hand and a "one up, two down" threshold algorithm determined the haptic force for the next level.

The algorithm converged at the 71% accuracy level[7]. The forces were decreased by 10% after each trial when the subject selected the correct icon and there had been a total of two or more consecutive correct responses. After every incorrect selection, the forces were increased to the previous level. The forces were unchanged for the first correct response after an incorrect response.

Each upward or downward slope was termed a “run”. An experiment contained ten runs. The last six force values at which the incrementations changed direction were averaged to determine the haptic threshold[3].

Before performing this experiment, each subject completed a training session to become familiar with the apparatus. This session was identical to the actual experiment with the following exception: Instead of ending after 10 runs, the session ended once the subject decreased the forces to 40 milliNewtons or completed 80 trials, (All subjects completed the training before the 80 trial cutoff.)

We recorded the time it took for each subject to complete the training session. Using these times as an index, the subjects were assigned matched pair counterparts. The matched pairs were relevant only for the second experiment.

2.2. Task Performance

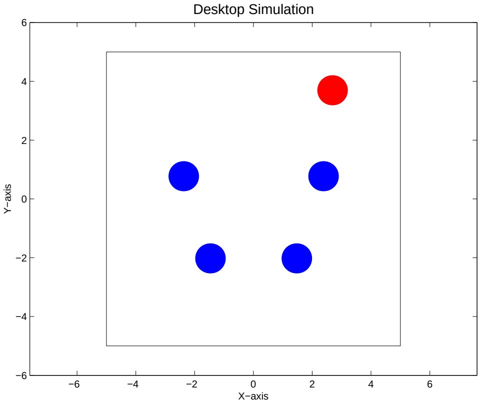

Figure 4. Screenshot of the arrangement used for the task performance enhancement experiment.

Five icons were placed in a specific arrangement with four blue and one red (Figure 4). The subject moved the end effector to the red icon and pressed a key. Once the key was pressed while the end effector was inside the target icon, a different icon then became red and the subject repeated the action quickly. The time between accurate key presses and amplitude of the path length were recorded.

The icons were arranged with exactly four possible path lengths; 2.94, 4.76, 5.85, and 7.07 millimeters. For instance, in the one dimensional case, there were four separate paths of the shortest length and one path of the longest length. This two dimensional arrangement preserved the same distribution of path quantities versus path lengths. Once again, this choice was made to preserve consistency with the one dimensional case.

Using the matched pair assignments, the subjects were split into two groups. One group performed the experiment with all the icons having haptic forces, the second group performed the experiment with force on only the red icon. There were separate segments of 100 trials for each of four levels of force; 0, 50, 100, and 300 milliNewtons. The segments were ordered at random to eliminate learning effects (matched pairs had the same ordering of forces).

This experiment was also preceded by a training session which consisted of 100 trials at 300 milliNewton. The training was identical to one segment of the experiment and there was no intermission between the training session and the experiment or between segments of the experiment.

3. Results

The data from all eleven students were included in the the threshold part of the study. In the performance enhancement experiment, though, only ten subjects’ data could be included since a matched companion was not found for one subject.

3.1. Haptic Threshold

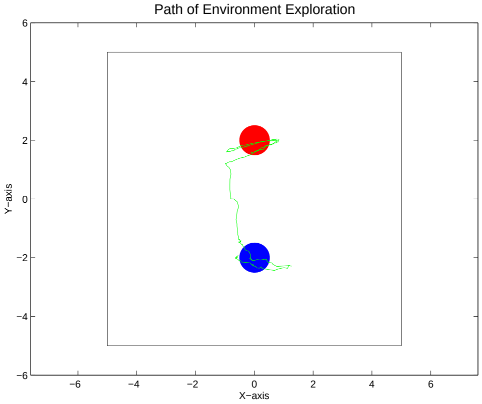

Figure 5. Example of a subject’s exploration of two icons.

The subjects palpated the desktop simulation by moving their finger in and out of the two icons until they could make a determination as to which icon had force. During

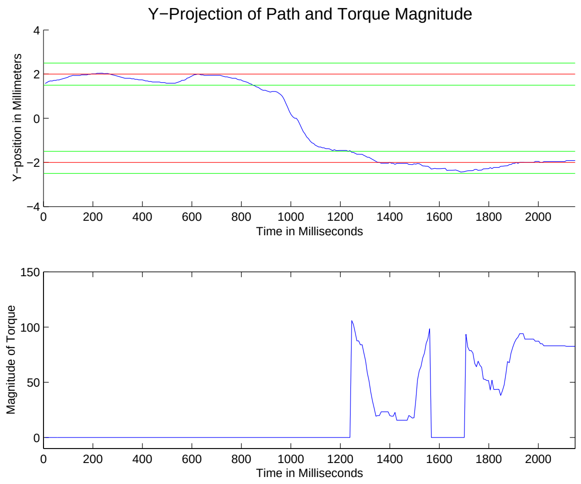

Figure 6. Y component of position (top) moves from icon without haptic feedback to one with haptic feedback. Magnitude of force applied to end-effector (bottom) varies only when subject is in second icon. Gap at $t = 1600$ indicates X-axis drift outside the icon (Figure 5).

one 100 milliNewton trial of every subject, end-effector position and the applied force magnitude data were recorded (Figures 5 and 6). Exploration behavior in the case shown included left-right movement across the icons on either end of a vertical movement between the icons. The subject first explored an icon without force $(0 < t < 800ms)$ and then with force up to 100 milliNewtons $(1200 < t < 2000ms)$ (Figure 6). The magnitude of the icon peak force and trial number were also recorded throughout the experiment (Figure 7).

Most participants completed this experiment in less than ten minutes and in generally between 50 and 70 trials. Nearly all subjects spent about ten seconds per trial identifying the icon which had force. The average haptic threshold of the eleven subjects was 20.8 milliNewtons.

3.2. Task Performance

Each pair of subjects completed complimentary experiments for all four force levels. The amount of time between accurate key presses, (MT), and the amplitude of the path length, (A), were recorded. Erroneous key presses were not.

With the width of the icon, (W), Fitts' Law can be applied and a line can be fit to the data using least squares, $y = a + bx$ (Table 1 and figure 8). This plot illustrates flatter slopes for higher forces. It can also be noted that the absence of haptic distractors decrease slope. (A flatter slope is a higher FIPR.)

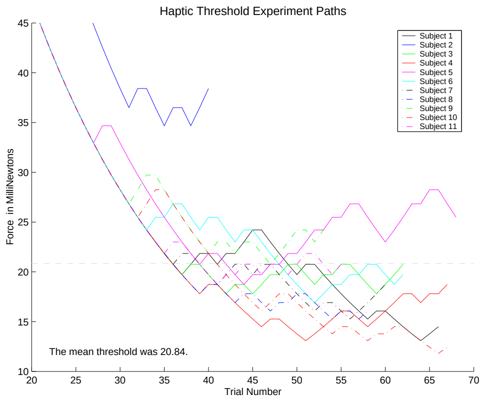

Figure 7. Force plotted against trial number for 11 subjects in threshold experiment. The mean haptic threshold was 20.8 milliNewtons.

Force	a	b	r^2
Force on all icons			
0mN	193.84	636.09	0.994
50mN	208.08	529.49	0.994
100mN	131.82	738.25	0.992
300mN	135.50	658.57	0.991
Force on one icon			
0mN	75.34	935.51	0.987
50mN	22.52	1026.27	0.982
100mN	16.69	996.99	0.982
300mN	11.12	951.02	0.981

Table 1. Least squares parameters of data from performance experiment where a is slope, b is the y-intercept and r^2 is the coefficient of determination.

Using the mean travel time, (MT_i), for each of the four distinct amplitudes, (A_i), the Fitts' Information Processing Rate (FIPR) can be calculated (Figure 9).

$$FIPR = \frac{\log_2(\frac{2A_i}{W})}{MT_i}$$

FIPR increased with increases in icon force magnitude for both conditions (force possessed by all icons or one icon). FIPR levels were higher for the group with force on one icon than for the group with forces on all the icons at all force levels by a small amount (0.1 to 0.5 bps), but we have not evaluated the statistical significance of this difference. The total increase in FIPR from 0 to 100 milliNewtons conditions was just under 0.2 bps for both groups.

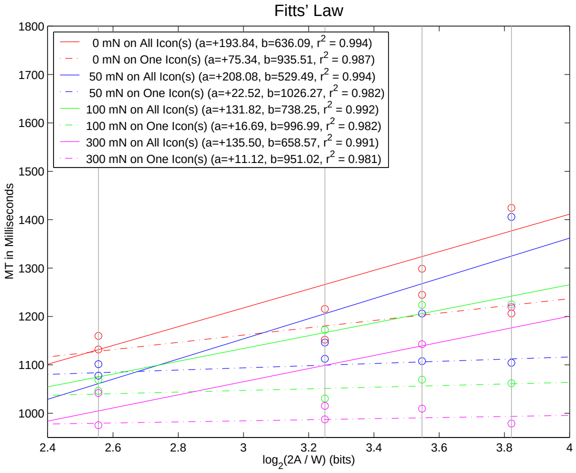

Figure 8. Fitts' Law curve for the 0, 50, 100, and 300nN force levels for both cases of task performance enhancement experiment. The vertical lines indicate icon placement.

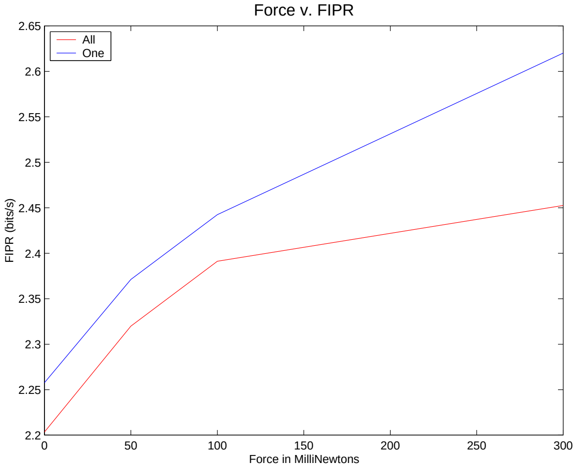

Figure 9. Maximum force on haptic icon plotted against the task's FIPR.

4. Discussion

The first experiment established that subjects may perceive very small forces through the Penbased Haptic Display (about 21 milliNewtons at 71% accuracy) when expecting to encounter them. This result, though, does not necessarily mean that such small effects help a user to perform a task since the user likely expends extra effort to detect such small forces for this study.

In the second experiment, which simulates a desktop icon-clicking task, small performance improvements of 0.1 bps were measured at haptic forces as low as 50 milliNewtons. This force is comparable to the weight of two U.S. dimes at rest.

It is interesting to compare these results to our earlier research[3] performing similar experiments in a 1-D haptic enabled environment. Our present threshold measurement of about 21 milliNewtons is lower by 5-10 milliNewtons than the threshold measured by Dosher et al. [3].

There are several possible explanations for this difference. First, the devices have different engineering characteristics including greater inertia and friction for the "Fingertip Haptic Display" used in the one dimensional experiments. Secondly, there may be fundamental differences in human sensitivity when the size of the workspace is smaller. Finally we may have an effect of icon size. The one millimeter icons of this study are smaller than the 3-5 millimeter icons of [3].

5. Future Work

With two dimensional interaction, there are many possible trajectories which the finger can trace to explore the circular icon. Our example shows the subject making left-right movements across the icons to detect force (Figure 5). It will be interesting to study the preferred direction – if any – used by subjects and whether it changes as forces are made smaller.

Understanding the haptic sensitivities in relation to orientation at low levels will likely yield a set of interesting properties. These properties may lend valuable insight into the design of efficient new haptic devices conforming to the low power, weight, and volume requirements of laptops, PDA's and even cell phones.

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